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Subway platform air quality: Assessing the influences of tunnel ventilation, train piston effect and station design

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HIGHLIGHTS

- Subway platform air quality varies depending on ventilation and station design.
- In some stations PM levels can double if tunnel ventilation is switched off.
- Accumulation of PM occurs at one end of the platform rather than in the middle.
- CO levels are low and controlled by traffic-contaminated air from street level.
- CO_2 variations depend on passenger numbers and train frequency.

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ABSTRACT

A high resolution air quality monitoring campaign (PM, CO_2 and CO) was conducted on differently designed station platforms in the Barcelona subway system under: (a) normal forced tunnel ventilation, and (b) with daytime tunnel ventilation systems shut down. PM concentrations are highly variable (6–128 $\mu gPM_1\ m^{-3}$, 16–314 $\mu gPM_3\ m^{-3}$, and 33–332 $\mu gPM_{10}\ m^{-3}$, 15-min averages) depending on ventilation conditions and station design. Narrow platforms served by single-track tunnels are heavily dependent on forced tunnel ventilation and cannot rely on the train piston effect alone to reduce platform PM concentrations. In contrast PM levels in stations with spacious double-track tunnels are not greatly affected when tunnel ventilation is switched off, offering the possibility of significant energy savings without damaging air quality. Sampling at different positions along the platform reveals considerable lateral variation, with the greatest accumulation of particulates occurring at one end of the platform. Passenger accesses can dilute PM concentrations by introducing cleaner outside air, although lateral down-platform accesses are less effective than those positioned at the train entry point. CO concentrations on the platform are very low ($\leq$1 ppm) and probably controlled by ingress of traffic-contaminated street-level air. CO_2 averages range from 371 to 569 ppm, changing during the build-up and exchange of passengers with each passing train.

1. Introduction

Commuting by underground rail is a transport mode pioneered in London 150 years ago and now used daily by over one hundred million people worldwide (Nieuwenhuijsen et al., 2007). Subway systems reduce road traffic congestion above ground and provide efficient transit that is generally viewed as environmentally friendly, offering what has been described as "the lifeline of urban development" (Pan et al., 2013). Despite the obvious benefits, however, it has become increasingly clear that many subway systems have a problem with regard to underground air quality and, as such, present a potential health risk to regular commuters and working staff (e.g. Karlsson et al., 2006), especially those already compromised by respiratory or cardiovascular disease. Inhalable particulate matter (PM) levels are typically much higher than those above ground, with published studies in subway systems from cities as varied as Los Angeles, Barcelona, Milan, Paris, Prague, Rome, Stockholm, Seoul, Shanghai and Taipei consistently reporting

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average PM_{10} levels on platforms that exceed 50 μg m^{-3} and in some cases reach 300 μg m^{-3} (Fromme et al., 1998; Johansson and Johansson, 2003; Seaton et al., 2005; Braniš, 2006; Ripanucci et al., 2006; Salma et al., 2007; Kim et al., 2008; Park and Ha, 2008; Raut et al., 2009; Ye et al., 2010; Cheng and Yan, 2011; Kam et al., 2011; Colombi et al., 2013).

The air quality of a given subway platform will depend on a complex interplay of factors such as the ventilation system, train speed and frequency, wheel materials and braking mechanisms, and station depth and design (Querol et al., 2012 and references therein). Air movements on the platform are influenced by periodic cycles involving three-dimensional turbulent flow through mechanically forced ventilation systems, draught relief outlets ("blast shafts"), and platform access points, driven to a large extent by the "piston effect" of the trains moving through the tunnels (e.g. Lin et al., 2008; Jia et al., 2009; Pan et al., 2013; López-González et al., 2014). In the latter process, the train passing through the tunnel has a dual effect by pushing the air in front of it and sucking the air behind into a negative pressure vortex in its wake, generating air currents of greater or lesser intensity depending on the speed of the train and the dimensions of the tunnel. A perceived virtue of these piston winds lies in their ability to ventilate the tunnels and platforms, thus possibly reducing the need for additional mechanically forced ventilation. Thus optimal use of the piston effect offers the possibility of making significant energy savings (Pan et al., 2013). In the city of Barcelona, for example, the subway system energy consumption can exceed 268 million kW h^{-1}, with ventilation systems consuming most of the 79 million kW h^{-1} related to non-traction electricity use (TMB, 2010 own data). However, another aspect of the interplay between the piston effect and mechanically forced ventilation in underground transport systems is the possible influence on platform air quality, although this aspect has been largely overlooked (Pan et al., 2013). With this in mind, we report on the results of a recent experiment conducted on platforms in the Barcelona metro system in which air quality was monitored across a range of station designs under (i) normal ventilation conditions, with mechanical forced ventilation running in the tunnels, and (ii) experimental ventilation conditions, when the forced ventilation of the tunnel was turned off during daytime so that the train piston effect was emphasized. During the two sampling periods we monitored ambient PM concentrations in different size fractions at high time resolution (every 6 s) and at different platform locations, along with coeval concentrations of CO and CO_2. The primary aim of the study was to analyze the degree to which station design and the train piston effect influence air quality on underground train station platforms and thus potentially impact on energy consumption and passenger health.

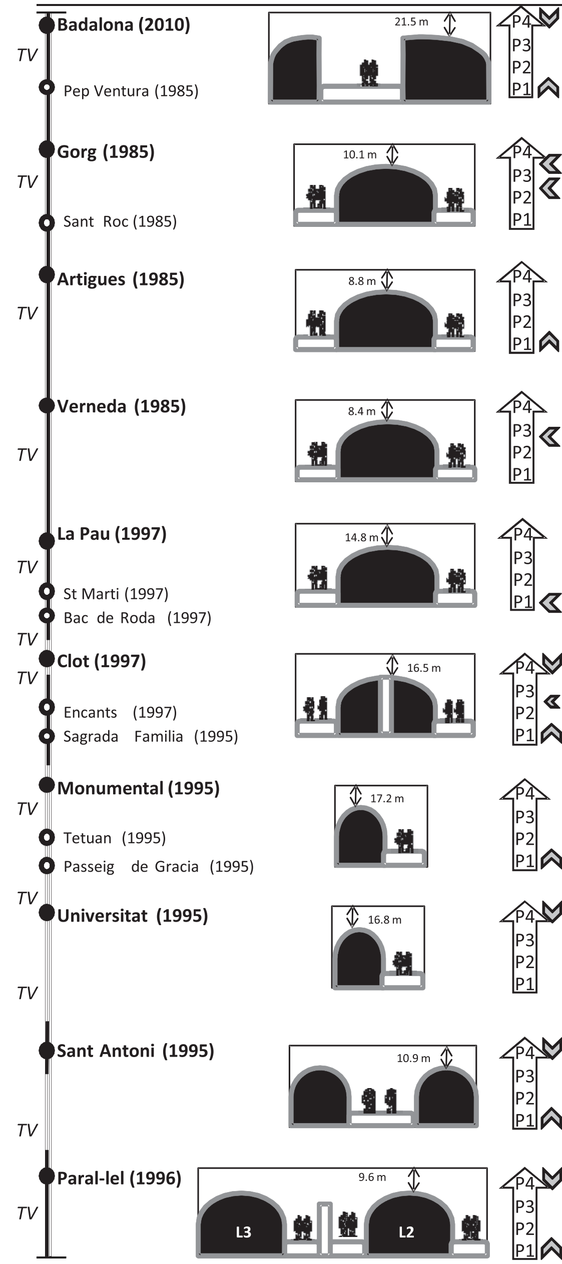
2. Methodology

Line 2 (L2) in the Barcelona Metro system was selected as our study target for the experiment because it has a wide variety of station designs and was constructed in different stages, culminating in the opening of the latest extension to the nearby municipality of Badalona in 2010 (Fig. 1). The line is 13.1 km long and has 18 stations, with trains circulating at an average speed of 27.6 km h^{-1} and crossing the city in a NE–SW direction almost parallel to the coastline and therefore with no major topographical gradients. The entire line runs underground, typically at depths of 10–20 m below the surface, with tracks built on concrete (with the exception of one station where ballast is used), and it operates using a rigid overhead catenary electric power supply. Measurements were carried out at 10 platforms from 14 to 27 January 2013, with stations being carefully selected to ensure that include different designs with regard to tunnel, railtrack and platform access points. As stated above, two different conditions were studied: from 14 to 20 January the ventilation system of the tunnels in L2 during working hours was normal (forced mechanical tunnel ventilation: FMTV), whereas it changed to experimental (no FMTV during daytime) from 21 to 27 January. The change was done during the weekend to allow conditions to stabilise before sampling. Ventilation in the platforms was kept the same during both periods. Measurements under these two contrasting conditions were performed at each selected station for 1 h, sub-divided into 15-min periods each at four positions approximately equidistant along the platform (numbered P1–P4, with P1 being the train entry point and P2–4 being progressively further away down-platform). Although it is clear that PM varies spatially along the platform (Querol et al., 2012), this protocol was adopted in order to investigate the possible reasons for these PM concentration variations at the 10 platforms. All measurements were carried out on subway platforms with trains travelling towards Badalona (NE direction) and only on weekday (Monday to Friday) mornings after the rush hour and prior to the lunchtime travel period.

Most of the monitored stations are served either by single track tunnels (Universitat, Monumental, and Sant Antoni) or by a wider double track tunnel with lateral platforms (La Pau, Verneda, Artigues, Gorg and Clot), as depicted on Fig. 1. Separated single track tunnels characterise much of the southwestern section of L2, especially the four contiguous stations between Universitat and Monumental (Fig. 1). Both Universitat and Monumental were inaugurated in 1995, have narrow platforms with only one end-access point and, in the case of Universitat, five spaced gaps connecting the two platforms. In the case of the double-railtrack stations, three of these (La Pau, Verneda, Gorg) have lateral access points on each platform, Artigues station has one single access located at one end of the platform, and Clot has two end accesses and a dividing wall separating the railtracks (Fig. 1). Whereas Verneda, Artigues and Gorg are the oldest stations on the line (opened in 1985), La Pau and Clot were opened in 1997 (Fig. 1). With regard to the end-of-line stations, Paral-lel has two end exits as well as lateral connections to an adjacent platform (Line 3), whereas the spacious, well-ventilated station of Badalona has two end access points and a third parking railtrack (Fig. 1).

The measuring equipment comprised: i) An optical particle counter Model 1108 (Grimm Labortechnik GmbH & Co. KG) measuring atmospheric PM concentrations (μg m^{-3}) in 15 different sizes of particles between 0.3 and 20 microns in diameter. For better visualization, the 15 channels results have been grouped into three, namely PM_{10}, PM_3 and PM_1, corresponding to particles smaller than 10, 3 and 1 micron in diameter respectively; ii) An indoor air quality analyzer IAQ-CALC, Model 7525 (TSI), which allows simultaneous measurement of continuous levels of carbon dioxide and carbon monoxide (CO_2 and CO) in parts per million (ppm).

Measurements were carried out simultaneously with a data collection interval of 6 s, the minimum time resolution offered by the equipment used, in order to test the effect of each train as it passes through each station. Levels of PM provided by the Grimm monitor were corrected after intercomparison with a reference high volume PM sampler after the study applying two factors, one for the PM_{10} size fraction ($y = 0.36x - 2$, $R^2 = 0.87$) and another one for both PM_3 and PM_1 ($y = 0.28x + 0.08$, $R^2 = 0.73$) data. Both factors were obtained by comparing PM automatic values with gravimetric data (14 and 7 PM_{10} and $PM_{2.5}$ filter samples respectively) from a referenced high volume sampler (MCV) collecting samples during the two weeks after the campaign. Measurements represent a total of over 1100 PM data per station. Also at each station a manual control of the exact time of arrival and departure of each train was registered, to check *a posteriori* correlations



Station	Platform	WITH forced tunnel ventilation: PM_1	PM_3	PM_{10}	CO_2	CO	WITHOUT forced tunnel ventilation: PM_1	PM_3	PM_{10}	CO_2	CO
Badalona (2010)	P4	6	17	33	393	<0.1	**9**	24	38	372	<0.1
	P3	6	17	**39**	391	<0.1	7	23	42	372	<0.1
	P2	8	16	33	386	<0.1	7	19	34	371	<0.1
	P1	8	**18**	33	393	<0.1	8	**25**	**59**	378	<0.1
		Av. PM_{10} =35 µg/m^3				<	Av. PM_{10} =43 µg/m^3				
Gorg (1985)	P4	70	194	220	444	0.3	72	224	301	434	0.6
	P3	78	217	258	450	0.4	**83**	**244**	**304**	440	0.6
	P2	79	223	254	443	0.5	75	213	275	445	0.6
	P1	**115**	**299**	**316**	455	0.6	62	176	221	454	0.6
		Av. PM_{10} =262 µg/m^3				<	Av. PM_{10} =276 µg/m^3				
Artigues (1985)	P4	**104**	**314**	**332**	426	<0.1	**68**	**200**	**218**	427	<0.1
	P3	38	109	126	417	<0.1	33	103	130	421	<0.1
	P2	52	147	163	407	<0.1	30	84	104	413	<0.1
	P1	29	80	93	398	0.1	37	92	101	418	0.1
		Av. PM_{10} =181 µg/m^3				>	Av. PM_{10} =137 µg/m^3				
Verneda (1985)	P4	97	201	273	484	0.1	87	183	222	463	0.3
	P3	88	184	252	488	0.1	**115**	209	237	559	0.2
	P2	88	189	237	456	0.2	101	184	210	569	0.2
	P1	**128**	**219**	**309**	451	0.2	114	**214**	**247**	557	0.3
		Av. PM_{10} =268 µg/m^3				>	Av. PM_{10} =230 µg/m^3				
La Pau (1997)	P4	**44**	**127**	**169**	425	0.1	**75**	**202**	**205**	427	<0.1
	P3	33	94	131	423	0.1	38	119	137	408	<0.1
	P2	29	71	112	437	0.2	19	51	74	422	<0.1
	P1	31	73	118	473	0.4	22	56	80	426	<0.1
		Av. PM_{10} =133 µg/m^3				>	Av. PM_{10} =120 µg/m^3				
Clot (1997)	P4	**52**	**119**	153	528	0.6	72	152	167	470	0.3
	P3	51	115	**157**	527	0.7	59	127	152	457	0.1
	P2	39	83	113	514	0.7	57	130	149	460	0.2
	P1	38	80	108	509	0.8	**111**	**262**	**268**	470	0.3
		Av. PM_{10} =130 µg/m^3				<<	Av. PM_{10} =184 µg/m^3				
Monumental (1995)	P4	29	74	90	426	0.6	**69**	**189**	**259**	461	0.6
	P3	30	75	91	428	0.6	61	147	173	473	0.6
	P2	33	85	97	430	0.6	63	148	170	480	0.7
	P1	**36**	**88**	**103**	446	0.8	67	152	168	487	0.7
		Av. PM_{10} =95 µg/m^3				<<	Av. PM_{10} =193 µg/m^3				
Universitat (1995)	P4	34	94	115	487	0.8	63	171	221	471	0.6
	P3	37	98	122	493	0.9	69	183	238	469	0.6
	P2	39	102	124	479	0.9	80	204	256	468	0.6
	P1	**44**	**109**	**135**	490	1.0	**84**	**225**	**282**	491	0.6
		Av. PM_{10} =126 µg/m^3				<<	Av. PM_{10} =250 µg/m^3				
Sant Antoni (1995)	P4	40	124	176	456	0.6	59	164	219	451	0.2
	P3	39	110	153	428	0.4	63	164	223	428	0.1
	P2	57	161	193	450	0.5	59	165	**255**	429	0.1
	P1	**81**	**225**	**295**	453	0.6	**73**	**188**	238	441	0.2
		Av. PM_{10} =205 µg/m^3				<	Av. PM_{10} =234 µg/m^3				
Paral-lel (1996)	P4	55	**115**	**156**	544	0.5	**60**	**125**	**150**	546	0.5
	P3	49	89	107	503	0.5	47	91	116	527	0.5
	P2	46	86	106	516	0.5	42	79	105	529	0.5
	P1	**57**	103	118	561	0.5	30	61	94	508	0.4
		Av. PM_{10}=122 µg/m^3				>	Av. PM_{10} =116 µg/m^3				

Fig. 1. Line 2 station position, design (indicating depth), and particulate and gas concentrations at platform monitoring sites (P1–P4) with and without forced mechanical tunnel ventilation. Locations of accesses to platforms are indicated with small arrows in the P1–P4 scheme. Particulate concentrations highlighted in grey are exceptionally high (>50 µg m^{-3} for PM_1, >100 µg m^{-3} for PM_3, and >200 µg m^{-3} for PM_{10}). The highest PM concentrations at each platform are highlighted in bold. See text for details. TV: Tunnel ventilation.

between the passing of trains and the variability in the concentrations of the studied parameters. Finally, coeval outdoor PM concentrations were monitored in an urban background station in Barcelona (Palau Reial).

3. Results

Overall PM concentrations averaged for all ten stations with forced mechanical tunnel ventilation (FMTV) operating are PM_1 = 50 µg m^{-3}, PM_3 = 124 µg m^{-3}, PM_{10} = 159 µg m^{-3}. These average figures rise when tunnel ventilation is switched off: PM_1 = 59 µg m^{-3}, PM_3 = 144 µg m^{-3}, PM_{10} = 178 µg m^{-3}. However, such global averages obscure the fact that levels of inhalable particulates vary enormously depending on the station design and platform location. Badalona was by far the cleanest station along the line, which can readily be appreciated from the concentrations of PM_{10}, PM_3, PM_1 recorded laterally along each platform and listed in Fig. 1. In some stations PM levels are 10 (PM_{10}) or even 20 (PM_1) times the minimum levels recorded in Badalona, with values ranging in all stations between 6 and 128 µg/m^3 for PM_1, 16–

314 μg m^{-3} for PM_3, and 33–332 μg m^{-3} for PM_{10}. Standard deviation values were up to 21–32% in PM_1 and PM_{10} values respectively, due to the occurrence of sudden, short time, increments in PM concentrations related to passenger's actions near the monitoring equipment. These exceptional values were not excluded from the data as they are representative of transient fluctuations in platform conditions. There is also some variability in PM size ratios (PM_1/PM_{10} = 0.2–0.4, average 0.3; PM_3/PM_{10} = 0.5–0.9, average 0.8), although the average values for both ratios are the same whether or not forced tunnel ventilation is operating (Table S1). Concentrations of CO_2 averaged 458 ppm with 15-min averages ranging from 371 to 569 ppm (Fig. 1). With regard to individual measurements (6-s average), the minimum CO_2 concentration recorded was 364 ppm in the best ventilated station (Badalona) whereas the maximum observed was 627 ppm in the busy station of Paral-lel. Levels of CO, also shown in Fig. 1, range from below detection limit (<0.1 ppm) to a maximum individual measurement (6-s average) of 1.7 ppm. A paired *t*-test was applied to all data and revealed statistically significant differences in all cases (Table S2). Given the variability of air quality revealed by these results, we now consider the data in more detail from the perspective of station design.

3.1. Platform particulate levels with single-track tunnels

Ambient average concentrations of PM_{10} measured under FMTV conditions in the two stations with a single tunnel and platform (Universitat and Monumental) show a relatively restricted range of PM_{10} concentrations (95–126 μg m^{-3}, Fig. 1). When the ventilation system was turned off however there was a doubling in PM_{10} levels (193–250 μg m^{-3}: Fig. 1). It is immediately clear that air quality in this spatially confined type of station is highly dependent on the presence of mechanically forced ventilation operating inside the tunnel. Despite this jump in PM concentrations, however, the presence or absence of FMTV had no significant effect on particle size ratios, with PM_1/PM_{10} and PM_3/PM_{10} values being 0.3 and 0.8 for both stations with or without tunnel ventilation. The third station of Sant Antoni, where the two single-railtrack tunnels serve a double platform, had lower air quality under normal FMTV conditions (PM_{10} = 205 μg m^{-3}) than the other two stations and worsened further (to 234 μg m^{-3}) when the tunnel ventilation was turned off. As seen previously, PM_1/PM_{10} and PM_3/PM_{10} ratios appear to be unaffected by ventilation conditions (0.3 and 0.7–0.8 without and with FMTV respectively, Table S1).

Our monitoring protocol of measuring at four different points along the station platform (P1–P4) revealed contrasting patterns of spatial variation in PM concentrations (Fig. 2). Highest concentrations of all three PM size fractions almost always occur at one end of the platform, i.e. at sampling locations P1 (train entry) or P4 (train exit). Apart from this obvious similarity, however, all three stations were different in their detailed spatial PM distribution. Universitat station shows a consistent linear increase in PM away from the single access point at P4 (train exit) so that the train entry point has the worst air quality whether or not the tunnel ventilation is operating (Fig. 2). In Monumental station, where the single access point is in location P1 (train entry), PM levels are highest at P1 under normal FMTV conditions but at P4 when the tunnel ventilation is turned off, especially in the coarser PM_{10} fraction which increases along the platform by >50% from 168 μg m^{-3} to 259 μg m^{-3}.

Another feature of the Monumental data is that close to the entry point the arrival of successive trains is clearly recorded as a regular rise and fall of PM_{10} concentrations (Fig. 3). Thus under normal FMTV conditions at P1 PM levels reach their maximum just before the arrival of the train as the piston wind blows into the station. Upon train entry PM levels drop rapidly to define a concentration trough as the pressure wave moves down the platform and draws cleaner air in behind it from the platform access point in P1. In contrast CO_2 levels rise due to the passenger build-up and exchange that occurs with each successive train (Fig. 3a). On train departure from the station PM air quality once again deteriorates as the platform access in-draught dilution effect declines and the train produces PM resuspension after passing through. This pattern is also discernible when tunnel ventilation is turned off, although in this case as shown on Fig. 3 the sampling was done slightly earlier than on other occasions and coincided with the end of the morning rush hour. The greater number of passengers at this time is reflected in an average 9% increase in CO_2 levels, and the increased train frequency produces a more erratic, rapidly varying pattern of PM levels (Fig. 3b). Once again, however, the drop in concentrations induced by access in-draught immediately after train entry is apparent (Fig. 3b). In the case of the neighbouring station of Universitat this dilution effect is not generated because here the access is at the train exit point (P4). The train arrival pressure wave dissipates into the greater air volume of the station without the opportunity to drag cleaner air down from outside via a passenger access tunnel. Although some air is sucked into the station through the P4 access as the train leaves, the overall effect is to produce poorer air quality at Universitat. We attribute the difference of around 30% in average PM_{10} concentrations between these two single-track tunnel stations as due to the design of the access points, and note that it is discernible whether or not tunnel ventilation is operating and irrespective of train frequency (Fig. 1).

Finally, the double tunnel station of Sant Antoni has two end-access points and under normal FMTV conditions shows highest PM concentrations at the train entry point (Figs. 1 and 2). Unlike in the simpler design of Monumental station, the movement of trains in both directions in Sant Antoni produces a complex airflow and there is no recognisably obvious pattern of train arrival and departure affecting air quality. When tunnel forced ventilation is switched off average PM_{10} levels rise by 15% but there is much less spatial gradient along the platform (Fig. 1).

3.2. Platform particulate levels with double track tunnel

Three of these stations (Verneda, Artigues and Gorg) were opened in 1985 and represent the oldest part of the line, whereas the other two (La Pau and Clot) were opened in 1997, with Clot having a dividing wall separating the two railtracks and platforms (Fig. 1). Average concentrations of PM_{10} in the three older stations under normal FMTV conditions are very high (181–268 μg m^{-3}), these being around double those measured in the narrower single tunnel/single platform stations of Universitat and Monumental (Fig. 1). Cessation of FMTV airflow in the three older stations, however, did not have the deleterious effect on air quality seen previously in the single track tunnel stations, with PM concentrations staying similar or actually declining once the tunnel ventilators were switched off. In the case of the newer stations of La Pau and Clot, average PM_{10} concentrations are lower under normal FMTV conditions (130–133 μg m^{-3}: similar to those with single-track tunnel). However, once the ventilation was shut down the two stations diverged in their behaviour: whereas PM_{10} in La Pau fell even further (to 120 μg m^{-3}, especially in the areas nearer to the access i.e. P1–P2), those in Clot rose by over 40% (Fig. 1). Thus it appears that, compared to the single-track platforms, the presence of a double-track and wider platform certainly does not improve air quality under normal FMTV (in fact, it can be much worse), but neither do conditions necessarily deteriorate further once tunnel ventilation is closed off, unless air circulation is inhibited by building a dividing wall between the two railtracks (as

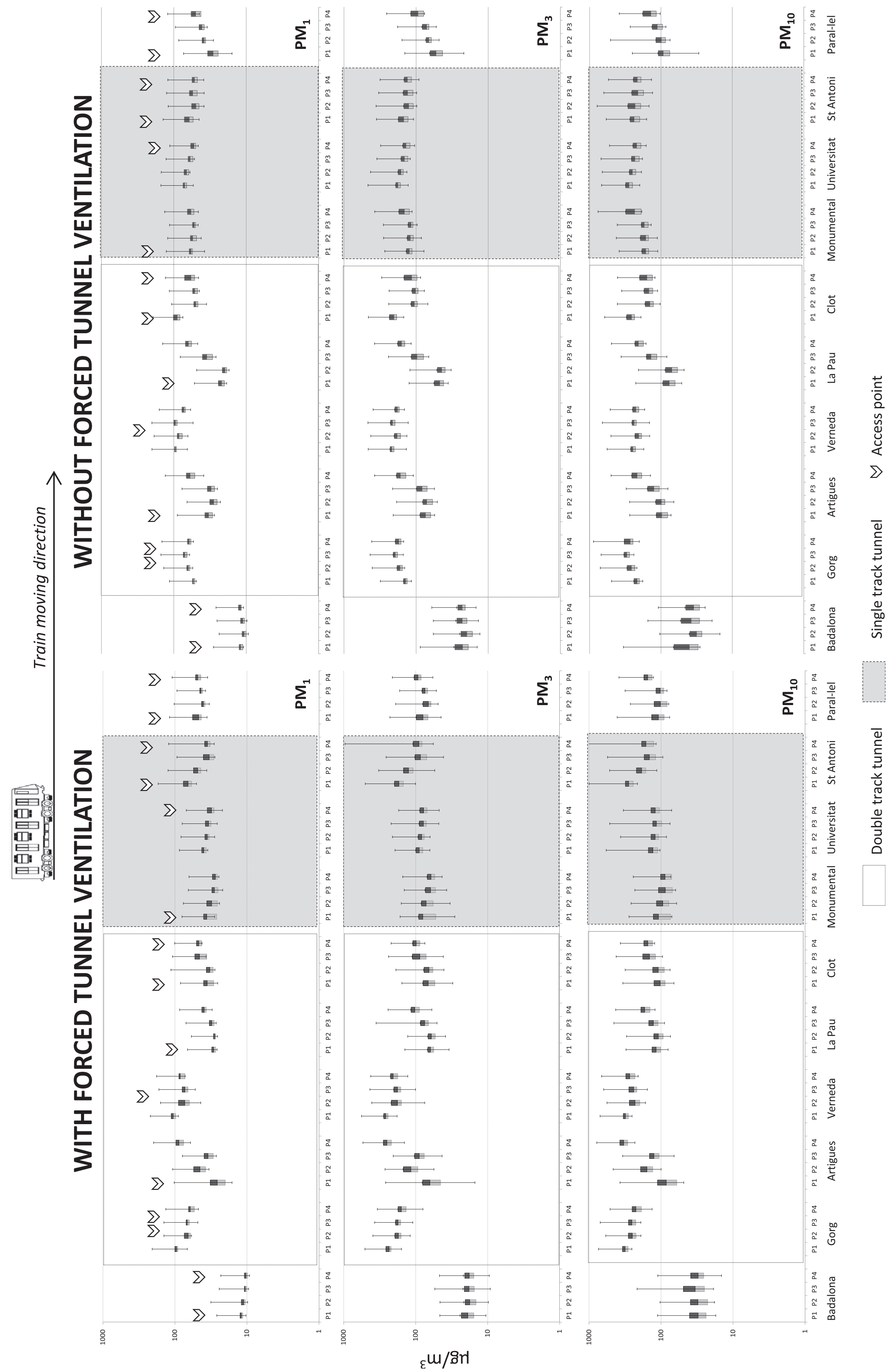


Fig. 2. Box and whisker plots displaying variations in PM_1, PM_3 and PM_{10} registered at locations P1 to P4 at each platform. The box encloses the 25 and 75 percentile range, with a line at the median value. Error bars have been calculated as the maximum value minus the percentile 75, and the percentile 25 minus the minimum value.

in Clot). Once again there is very little difference in average size profiles under the two ventilation conditions, with average PM_1/PM_{10} and PM_3/PM_{10} ratios being 0.3 and 0.8, respectively (Table S1).

With regard to spatial variations along the platform (Fig. 2), under normal FMTV conditions the PM peak always occurs furthest from the access point (excluding Clot which has two access points: Figs. 1 and 2). Without tunnel ventilation, however, this simple

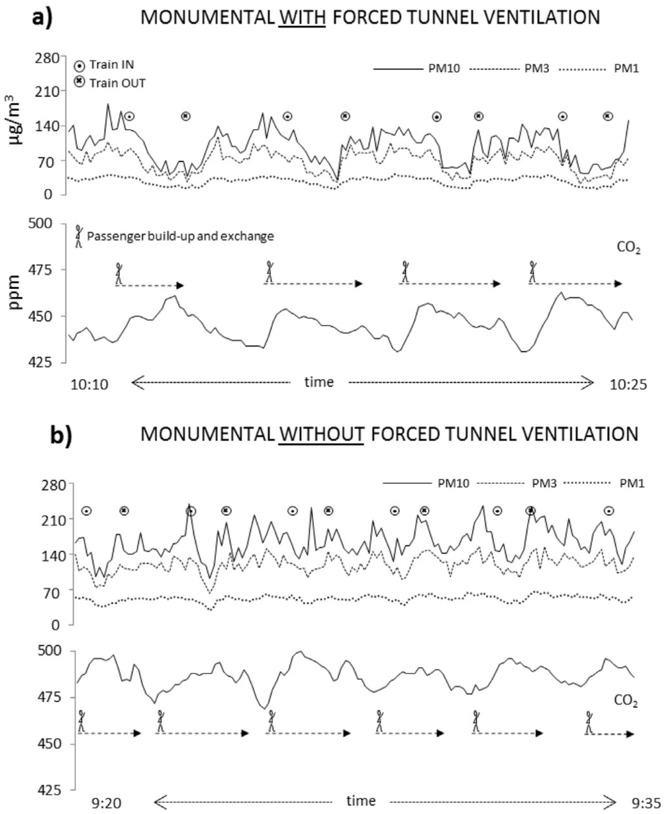


Fig. 3. Particulate matter and carbon dioxide concentrations measured at platform location P1 (train entry) in Monumental metro station under normal (3a: with FMTV) and experimental (3b: without FMTV) conditions. Note the drop in PM concentrations in response to the piston effect of train arrival when air is sucked into the platform via the adjacent passenger access tunnel, and the regular rise and fall of CO_2 concentrations due to passenger build-up and exchange with each passing train. The measurements without FMTV (3b) were made slightly earlier in the morning when there were more trains and passengers and therefore higher CO_2 levels.

pattern is superimposed by a tendency for PM levels to increase close to lateral access points (see Verneda and Gorg on Fig. 1). This effect is strongest in Gorg where there is a double lateral access, each on either side of P3 where PM levels correspondingly peak (Figs. 1 and 2). Another difference is that stations with access points at train entry point P1 (i.e. La Pau and Artigues) show the most extreme spatial gradients along the platform to P4. In the case of Clot station, which has two end-access points and a mid-platform lateral access to a connecting line, there is a major difference between normal FMTV and no FMTV (Fig. 1). Under normal FMTV conditions PM levels peak at P4 whereas when the tunnel ventilation is deactivated there are increases at both ends of the platform, especially at P1. Finally, once again as noted for Sant Antoni, the complex air movements induced by opposing train directions in these double-track stations do not produce any regular rise and fall of PM levels that can be related to train arrival and departure.

3.3. Terminus stations

The two end-of-line stations are very different in terms of their design and air quality. Both have two end-platform exits and a double railtrack tunnel, but in the case of the older station of Paral-lel (1995) there are open lateral connections with the adjacent and busy Metro Line 3, whereas in the newer (2010) station of Badalona there is a third "parking" rail (Fig. 1). Being the deepest of all the L2 stations, Badalona station is equipped with no less than seven ventilating fans as opposed to the other stations which have only one, two, or (in the case of Paral-lel) three. In terms of air quality Badalona consequently offers a complete exception to the other stations. The new platform ventilation system is fiercely effective and combines with the unusually spacious station design to produce exceptionally low levels of average underground PM_{10}, with or without the presence of forced tunnel ventilation (35–43 $\mu g\ m^{-3}$: Fig. 1). This design is reflected in the particle size ratios of Badalona compared to the other stations with a higher proportion of coarse particles (0.2 and 0.5 for PM_1/PM_{10} and PM_3/PM_{10} with and without forced tunnel ventilation, Table S1). In contrast, Paral-lel has more similar PM concentrations to the coeval double railtrack station of La Pau (Fig. 1). Also as with La Pau, switching off the tunnel ventilation at Paral-lel produces no significant difference in ambient PM concentrations, although it does produce a more organised linear increase in levels from P1 to P4 (Figs. 1 and 2).

3.4. CO_2 and CO concentrations

Levels of CO_2 measured at 6-s intervals varied from a minimum value of 364 ppm at one end of the line (in the well ventilated, spacious and less crowded station of Badalona) to 627 ppm at the other (in the congested, central urban station of Paral-lel). Average concentrations of CO_2 on platforms mostly lie within the more restricted range of 410–520 ppm, this being higher than coeval Mauna Loa CO_2 values for late January 2013 (396 ppm) but comparable to concentrations recorded from many urban street-level sites worldwide (e.g. Grimmond et al., 2002; George et al., 2007; Idso et al., 2013) and average values measured in the Taipei, Seoul or Los Angeles subways (Cheng and Yan, 2011; Bong et al., 2013; Kam et al., 2011). Eliminating tunnel ventilation had no consistent effect on platform CO_2 levels, which are related more to the spatial position of access points and the rhythm of train arrival and departure (Fig. 3) where and when the increase in number and respiratory activity of passengers produces higher exhalation gas concentrations. The most marked example of this is displayed by the data at Verneda without tunnel ventilation where CO_2 levels close to the access point (P2–P3) rose >20% than those at the far end of the platform (P4), but a similar pattern (albeit usually varying much less than 10%) can be detected in almost all the other platform data.

Levels of CO averaged over the 15 min monitoring intervals are very low but vary across an order of magnitude from <0.1 to 1 ppm, with the highest values usually being found at the train entry point (P1). These levels are similar to those observed in Taipei (Cheng and Yan, 2011) but much lower than the 8 ppm levels registered in the Mexico subway (Gómez Perales et al., 2004). In Barcelona the CO peak can coincide with a PM peak and passenger access point (e.g. Monumental, FMTV), but this is much less common than for CO_2. In other cases (e.g. Universitat, FMTV) the CO peak again occurs in the same platform area as the PM peak, but at the opposite end to the platform access point. Lateral gradients in CO concentrations along the platform are also less common than with CO_2, and usually associated with normal FMTV conditions (e.g. Gorg, La Pau, Clot, Universitat). When the tunnel ventilation is turned off this gradient is lost. The highest CO levels observed (0.8 ppm or higher) occur only in the three most spatially confined stations (Universitat, Monumental, and Clot) at location P1 and under normal FMTV conditions, so once again station design and tunnel ventilation appear to be having an influence (Fig. 1).

4. Discussion

Published reviews of subway air quality reveal a wide range of PM concentrations present in underground platforms studied across the world, and beg the question: why is there such diversity? The data we provide here on the Barcelona L2 line offer some answers to this question, given that normal PM concentrations along this one line range from what can be considered acceptable compared with these other international subway systems (i.e. platform PM_{10} around 35 μg m^{-3} at Badalona) to very high (i.e $PM_{10} > 250$ μg m^{-3} at Gorg and Verneda). Average PM size ratios are quite similar for all stations, with the most marked differences being shown in the end-of-line stations (Table S1). The different ventilation systems operating in these two termini are reflected in much lower PM_1/PM_{10} and PM_3/PM_{10} ratios for Badalona (with and without FMTV) whereas in Paral-lel the PM_1/PM_{10} is higher than in any of the other platforms. There is very little variability between single and double-track stations, with values ranging from 0.3 to 0.4 PM_1/PM_{10}, and 0.7–0.9 PM_3/PM_{10} for double track stations and 0.3 PM_1/PM_{10} and 0.7–0.8 PM_3/PM_{10} for single track stations. Within each station the only spatial difference observed in these ratios is an increment of the PM_1/PM_{10} values (only under FMTV conditions) at the entrance point of the train into the station (0.34 average) which may be related to the preferential removal of coarser particles by the turbulence created by trains entering the station (Table S1).

Overviewing the data it is immediately clear that station design has a major influence. The station of Badalona, despite being much deeper than all the others, has by far the best air quality because it is new, spacious, strongly ventilated by 7 fans, and has two wide access points at opposite ends of the platform. At the other extreme the two stations with the poorest air quality are old and have lateral accesses located well away from the train entry point (Verneda and Gorg: Fig. 1). The position of the passenger access tunnel seems to be important here. The two stations of Artigues and La Pau are similar to Verneda and Gorg in their double-track design but they have platform accesses at the train entry point P1 and correspondingly show 30–50% lower PM concentrations (Figs. 1 and 2). Furthermore, the lowest platform PM concentrations at Artigues and La Pau coincide with the access tunnels, suggesting that, as with the Monumental results, combining a platform access with the train entry point aids the advective cleansing of the station airmass by drawing air in from above ground.

During our January experiment, street level atmospheric conditions in the city were unusually clean (urban background $PM_{10} < 20$ μg m^{-3}), so the dilution effect of drawing air underground would have been at its greatest. In fact, outdoor air was actually cleaner during the second phase of our underground experiment (no FMTV) when platform conditions were generally worse (outdoor urban background = 17, 12 and 9 μg m^{-3} compared to 12, 9 and 7 μg m^{-3} of PM_{10}, $PM_{2.5}$ and PM_1 respectively during the weeks with and without FMTV, a decrease of around 25%: (Fig. S1). We can conclude from this that rising concentrations measured in the subway stations after switching off forced tunnel ventilation was not related to the infiltration of outside air.

Another station configuration that appears to produce worse air quality is that where two single tunnels converge to serve one central island platform, as is the case in Sant Antoni (Fig. 1). It would appear that in the complex airflow pattern created by this design neither the forced ventilation in the tunnels nor the train piston effect are capable of working together to prevent the build-up of inhalable particles on the platform, despite the presence of two end-access points. In contrast, having two end-access points but with a wide double railtrack tunnel instead of two narrow single track tunnels results in much better air quality. Thus both Paral-lel and Clot show PM concentrations of 120–130 μg m^{-3} under normal FMTV conditions, some 40% lower than that in Sant Antoni (Fig. 1). The effect of train arrival on PM concentrations in the station was most clearly visible at the train entry point in Monumental (a single-track station), in agreement again with a stronger influence of the piston effect in the concentrations of PM in this type of station.

Our data on gaseous pollutants also show a clear tendency for concentration peaks to occur at one or both platform ends and commonly close to an access tunnel (Fig. 1). Underground CO levels are generally extremely low, with highest levels being recorded in the southwestern part of the line, between Paral-lel and Clot (Fig. 1). This section of the line passes beneath the busy, traffic-congested central part of the city, and values of up to 1 ppm CO presumably reflect indraw of this gas from street level. The fact that concentrations of this gas are normally higher under normal FMTV conditions (compare for example Sant Antoni, Universitat, Clot on Fig. 1) suggests forced ventilation-enhanced CO entry from traffic-contaminated air above ground. In contrast, platform CO_2 concentrations are controlled more by underground conditions, fluctuating in response to variations in passenger density and movement. To our knowledge the subtle rise and fall of CO_2 levels in response to passenger build-up and exchange (Fig. 3) with each passing train has not been directly observed and published previously, and presumably occurs in all single track metro designs worldwide.

Finally, one motive for the conduction of our experiment was to test whether energy savings achieved by switching off tunnel ventilation could be further justified by observing improved air quality. As shown in Table 1 in the single track tunnel stations this is not the case, with platform air quality suffering a severe deterioration once the tunnel ventilators were deactivated, especially in the finer grain size fractions. On the other hand, this deterioration was not observed in most of the other stations, with double-track tunnel stations showing averagely similar values with and without forced ventilation (Table 1), with Artigues, Verneda, La Pau and, to a minor extent, Paral-lel, having actually an improvement in PM levels under no FMTV. Thus, from the perspective of air quality and energy savings (but perhaps not when considering heat dissipation or PM dispersal), there may indeed be a case for reducing forced ventilation in the larger diameter double-track tunnels, especially in those stations located in more air polluted urban areas, without compromising the overarching objective of cleaner air for underground commuters.

5. Conclusions

- Our results from Barcelona's subway L2 demonstrate that platform air quality within the same line of an underground rail system can vary from reasonably low ($PM_{10} < 35$ μg m^{-3}: approaching Interim Target 3 of the WHO outdoor air guideline)

Table 1
Average PM concentrations with and without mechanical forced ventilation at main groups of stations.

	Badalona			DOUBLE-track tunnel			SINGLE-track tunnel			Parallel		
	PM_1	PM_3	PM_{10}	PM_1	PM_3	PM_{10}	PM_1	PM_3	PM_{10}	PM_1	PM3	PM_{10}
With FMTV	7	17	35	64	159	195	41	110	140	52	99	122
Without FMTV	8	23	43	66	161	190	68	175	225	45	89	116

to high ($PM_{10} > 250\ \mu g\ m^{-3}$), depending on ventilation conditions and station design.
- Narrow platforms with single-track tunnels are heavily dependent on forced tunnel ventilation to maintain relatively low PM concentrations. The train piston effect alone in this type of station is not enough to stop PM levels from doubling when tunnel ventilation is switched off.
- In contrast, air quality in wider stations with spacious double-track tunnels can actually improve when tunnel ventilation is switched off, offering the possibility of significant energy savings. This is not the case however for platforms served by two separated narrow tunnels, a design that appears to result in poorer air quality than that involving one tunnel alone.
- PM size ratios for all stations average 0.3 for PM_1/PM_{10} and 0.8 for PM_3/PM_{10} and remain unchanged whether or not forced tunnel ventilation is operating.
- There can be considerable lateral variation in PM concentrations along subway platforms, with the greatest accumulation of particulates usually occurring at one end of the platform rather than in the middle. Passenger access tunnels can dilute platform PM concentrations by introducing cleaner air from outside the station, with lateral accesses being less effective than those at the platform end, and those positioned at the train entry point inducing more effective dilution (during train arrival) than those near the train exit point.
- Concentrations of CO in the Barcelona metro are very low, although varying by an order of magnitude and probably controlled by the amount of traffic-contaminated air being brought down from street level.
- Average CO_2 levels measured at four different points along each of the ten platforms monitored range from 371 to 569 ppm. Where airflow is relatively simple, such as in narrow single-track platforms with one access at the train entry point, it is possible to detect a regular rise and fall of CO_2 produced by the build-up and exchange of passengers with each passing train. The amplitude of such variations will depend on passenger numbers, train frequency, and therefore time of day.

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Appendix A. Supplementary data

Supplementary data related to this article can be found online at http://dx.doi.org/10.1016/j.atmosenv.2014.04.043.

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